(Two) Open Questions in Stellar Nuclear Physics [1]

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Abstract. No doubt, among the most exciting discoveries of the third millennium thus far are **Oscillations of Massive Neutrinos** and **Dark Energy** that leads to an accelerated expansion of the Universe. Accordingly, Nuclear Physics is presented with two extraordinary challenges: the need for precise (5% or better) prediction of solar neutrino fluxes within the Standard Solar Model, and the need for an accurate (5% or better) understanding of stellar evolution and in particular of Type Ia super nova that are used as cosmological standard candle. In contrast, much confusion is found in the field with contradicting data and strong statements of accuracy that can not be supported by current data. We discuss an experimental program to address these challenges and disagreements.

INTRODUCTION

During the last few years extraordinary discoveries in fundamental Physics were made using stellar objects as close as the sun, and as far away as the most distant Type Ia supernova (SNeIa) at the far end of the observed Universe. These discoveries have fundamentally altered our view of the observed universe and hint that yet several more discoveries are soon to come. They were possible in part due to advances in Stellar Nuclear Physics, but they demand yet even higher precision of our knowledge of stars. The Standard Solar Model (SSM) [1] has been confirmed and the three decade persistent "solar neutrino problem" was solved by introducing neutrino oscillations [2]. The ^8B solar neutrino flux was measured with 7.3% accuracy [3] and extracted from a global analysis of solar and reactor neutrino experiments [4] with 4% accuracy. Type Ia supernova (SNeIa) were used as standard cosmological candles [5] and a recent acceleration in the expansion rate of the universe was suggested [6]. The suggested accelerated expansion was confirmed by the WMAP experiment to arise from dark energy that constitute approximately 70% of the observed universe [7].

THE STANDARD SOLAR MODEL

The Standard Solar Model is dependent on nuclear inputs and the most critical ones are cross sections of nuclear reactions [8] at solar conditions of central temperature of 15.7 MK and central density of approximately 150 g/cm^3. The two most important

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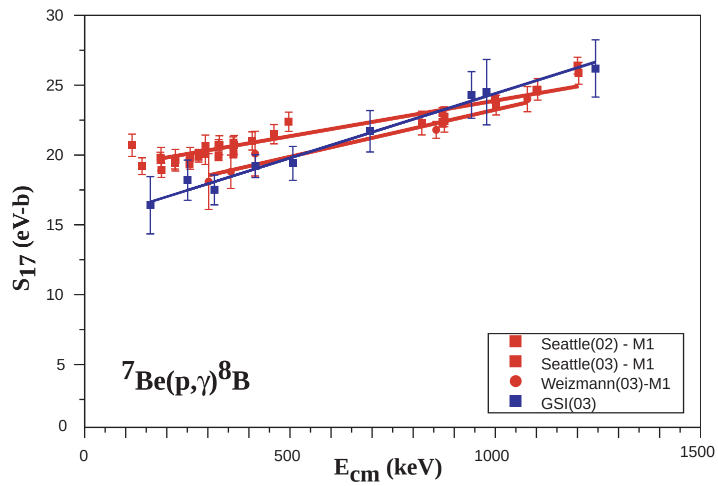

FIGURE 1. A comparison of the GSI [9], Weizmann [10] and Seattle [11] measurements of the astrophysical cross section factor S_{17} of the $^7Be(p,\gamma)^8B$ reaction, as defined in [8] and discussed in the text.

reaction cross sections that must be measured with an accuracy of 5% or better are the $^7Be(p,\gamma)^8B$ reaction and the $^4He(^3He,\gamma)^7Be$ reaction and the corresponding $S_{17}(0)$ and $S_{34}(0)$ defined in Ref. [8].

A major effort on measuring $S_{17}(0)$ with high accuracy was carried out in several labs and agreement among high precision data collected at GSI [9], Weizmann [10] and Seattle [11] was found. Most amazing is the excellent agreement between the Weizmann data that were measured with a ^7Be target and the GSI data that employed the Coulomb dissociation method. However as shown in Fig. 1 the slopes of these three results are sufficiently different. The d-wave correction to $S_{17}(0)$ on the other hand is directly related to this slope, and thus it is ill determined. Since the d-wave correction reduces $S_{17}(0)$ by as much as 15%, it precludes an accurate extrapolation of $S_{17}(0)$. This conclusion contradicts the strong statement of the Seattle group [11] that $S_{17}(0)$ has been determined with a theoretical uncertainty of 2.5%. This issue must be resolved by future high precision measurements of the slope, most likely with ^7Be beams [12], so as to allow accurate (5% or better) extrapolation of $S_{17}(0)$.

In contrast to the intensive work on $S_{17}(0)$, no progress what-so-ever was achieved on measuring $S_{34}(0)$ with high precision, and it is still poorly known with an error of 9% [8]. This inadequate situation must be improved in the near future as we expect the direct detection of ^7Be solar neutrinos. These measurements will conclude a four decade long quest by Nuclear Physicists for the nuclear inputs to the SSM. When the controversy on the composition of sun (Z/X) will also be resolved [13], it will allow high precision prediction of all solar neutrino fluxes including the ^8B neutrino flux. The high precision on one hand may provide a strong evidence for the SSM, but may also allow for a study of fundamental neutrino processes including oscillation to sterile neutrinos.

HELIUM BURNING AND THE C/O RATIO

The C/O ratio at the end of helium burning is still poorly known, twenty years after it was declared by Willie Fowler the "holy grail" of Nuclear Astro-Physics [14]. This parameter is essential for almost all aspects of stellar evolution of massive stars, and most recently it was also suggested to be essential for understanding the light curve of SNeIa [15]. The finding of Hoeflich were recently challenged [16], but the C/O ratio is most certain to play a major role in our understanding of the Phillips empirical relationship of peak luminosity and the shape of the light curve of Type Ia supernova [5]. Since the Phillips relationship is at the very foundation of using SNeIa as standard cosmological candle it is essential to understand it. The new generation of dedicated space telescopes that will solely measure Type Ia supernova makes it very important to understand SNeIa.

In order to measure the C/O ratio at the end of helium burning the cross section of the $^{12}C(\alpha,\gamma)^{16}O$ needs to be known at approximately 300 keV, but thus far it was measured only down to approximately 1.2 MeV. The extrapolation of this cross section to stellar energies (300 keV) is particularly difficult due to the substantial contribution from bound states. The properties of the bound states and their interference with quasi-bound states were thus far determined with the use of R-matrix theory. However, it now appears that the claimed accuracy of the R-matrix fits can not be substantiated. While the TRIUMF group quote an E1 astrophysical cross section factor with 25% uncertainty [17], Hale extracts a value that is eight times smaller [18]. Similarly elastic scattering data was used by the Notre Dame group to extract the E2 S-factor with the claimed 20% accuracy [19]. But this analysis in of itself was criticized for lack of theoretical foundation [20], and the result turned out to be a factor of 2.5 smaller than extracted by the Stuttgart group [21] that used R-matrix theory to extrapolate angular distribution data of the $^{12}C(\alpha,\gamma)^{16}O$ capture reaction itself.

A most promising new approach to measure both the E1 and E2 astrophysical cross section factors of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at energies as low as 700 keV emerged with the use of the High Intensity γamma Source (HIγS) at the TUNL lab at Duke [22]. In this experiment one will study the photodisintegration of ^{16}O with an Optical Readout Time Projection Chamber (TPC). The anticipated results of the HIγS facility are shown in Fig. 2, as compared to the disagreeing results discussed above.

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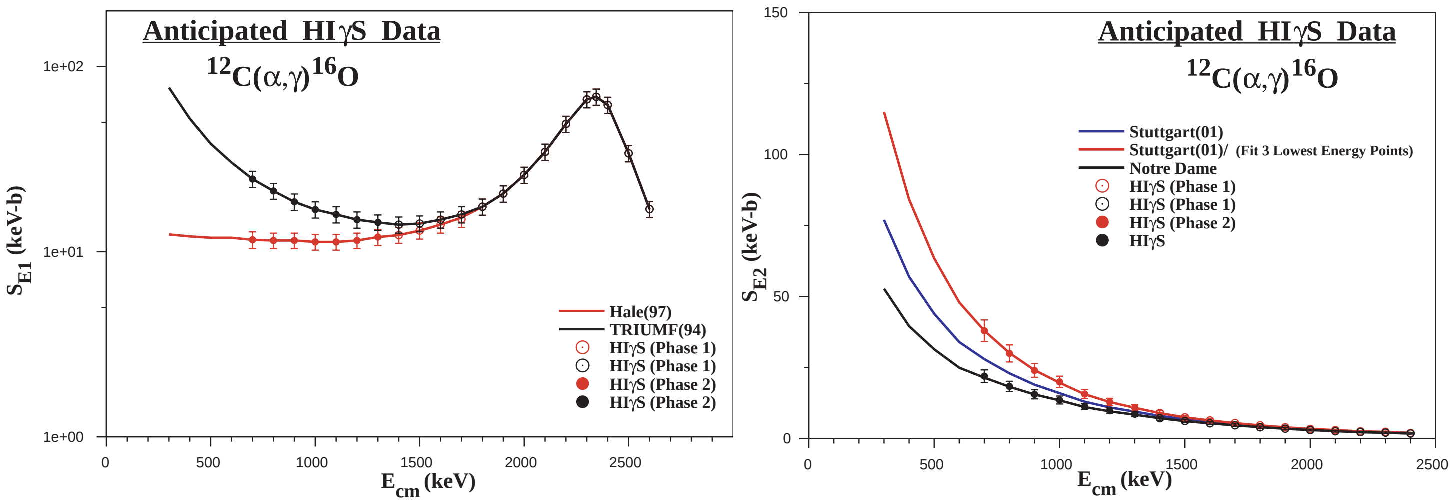

FIGURE 2. Anticipated HIγS data on the E1 S-factor as compared to the values quoted by the TRIUMF collaboration [17] and Hale [18], and on the E2 S-factor as compared to the results of the Notre Dame [19] and the Stuttgart groups [21].

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